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(19)

(54) FLOATING STRUCTURE

(71) We, AMOCO PRODUCTION COMPANY, a Corporation of the State of Delaware, United States of America, whose full post office address is 4502 East 41 Street, Tulsa, Oklahoma, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a structure floating on a body of water. More particularly, the invention relates to a floating structure from which drilling or production operations are carried out. In its more specific aspects, the invention concerns a floating structure having buoyancy means placed with respect to the trough of a design wave so as to minimize mooring forces imposed on vertical elongated members which anchor the structure, such as those forces which may be caused by passing waves.

In recent years there has been considerable attention attracted to the drilling and production of wells located in water. Wells may be drilled in the ocean floor from either fixed platforms in shallow water or from floating structures or vessels in deeper water. The most common means of anchoring fixed platforms include the driving or otherwise anchoring of long piles in the ocean floor. Such poles extend above the surface of the water with a support or platform attached to the top of the piles. This works fairly well in shallow water, but as the water gets deeper, the problems of design and accompanying costs become prohibitive. In deeper water it is common practice to drill from a floating structure.

In recent years there has been some attention directed toward many different kinds of floating structures, for the most part maintained on station by conventional spread catenary mooring lines, or by propulsion thruster units. One such structure for mooring is employed in the so-called vertically moored platform. A key feature of this structure is that the floating platform is connected to an anchor base only by elongate parallel members. The members are held in tension by the excess buoyancy of the platform. This offers a remedy for one of the major problems arising in the conduct of drilling, or like operations from a floating structure. This major problem is that ordinary hull-type barges or vessels, in response to ocean waves, may exhibit substantial amounts of vertical heave and angular roll motion. Such motions significantly hinder drilling operations. Motion difficulties are alleviated to a degree by use of so-called semi-submersible vessels or structures in which the floatation buoyancy is provided by long, slender vertical bottles or tanks. This design suffers the inconvenience that, if carried to the logical extreme of having but very little water plane area, the unit would become statically unstable, requiring careful reballasting to offset changes in vertical loads, such as the drilling hook load (e.g., when pulling the drill pipe, etc.) or changes in the weight of supplies. Some of these problems are eliminated or at least reduced in a vertically moored platform. Being subjected to tension, the elongate parallel members of the vertically moored platform are substantially inextensible and therefore restrain the platform to move primarily in the horizontal direction. This virtually eliminates heave and roll motions. In vertically moored structures heretofore considered, exceptionally strong moorings would be required to resist the vertical forces which might be imposed upon structure by the orbital motion of passing waves.

The present invention is concerned with minimising the mooring forces imposed by the structure on the elongated members, such as those caused by passing waves.

[*Price 25p*]

According to the present invention there is provided a floating structure having limited lateral movement for use in a body of water having an expected maximum wave, said structure comprising a platform including a working deck, and buoyancy means for supporting said working deck, anchor means for securing the structure to the floor of said body of water, horizontally spaced-apart, parallel, elongated members anchoring said platform to said anchor means, said platform in use being free of any anchoring connection with the floor of the body of water other than said parallel elongated members, said buoyancy means having a first volume below the still water line and above the trough of said expected maximum wave, said first volume having a cross-sectional area obtained by dividing the said first volume by the depth of the trough, and a second volume below the trough, said second volume being equivalent to a third volume and a fourth volume, said third volume being equal to the vertical dimension of said buoyancy means below the trough times said cross-sectional area, said fourth volume being equivalent to the second volume minus the third volume, and said fourth volume volume being between about 20 and about 60 percent of the total displacement of the buoyancy means.

Briefly, a preferred embodiment of this invention concerns a floating structure having limited lateral movement for use in a body of water. It is especially designed for an expected maximum wave. This expected wave is usually called the "maximum design wave". The structure includes a working platform supported by a buoyancy means comprising a plurality of slender vertical float members. The float members are anchored to the ocean floor by a plurality of horizontally spaced-apart, parallel elongated members. The volume of the buoyancy means can be defined as comprising two parts, the first part resulting from a straight, vertical, columnar shape which runs the entire vertical length of each vertical float member. The volume of the columnar portion comprises from about 40% to about 80% of the total displacement of the buoyancy means below the "still water" line. The ratio of the displacement of the columnar portion to the total displacement is called the columnar ratio p. A second volume of displacement surrounds the columnar portion and comprises the remainder of the total displacement. This second volume is to be located below the trough of the design wave. This critical placement of the second or auxiliary volume and the critical size minimizes the critical mooring forces imposed on the vertical elongated members by the structure due to the orbital motion of the passing waves. The first volume would have a cross-sectional area obtained by dividing the first volume by the depth of the trough. The second volume is positioned below the trough and is composed of a third and fourth volume with the third volume being equal to the vertical dimension of the float member below the trough multiplied by its cross-sectional area. The fourth volume would be equal to the second volume minus the third volume and would constitute between about 20 and 60 percent of the total displacement of the float member.

The invention will be better understood from the following detailed description taken in conjunction with the drawings, in which:—

Figure 1 is a view of a floating structure constructed in accordance with a preferred embodiment of the invention;

Figure 2 illustrates a perspective view of a part of one of the vertical floats shown in Figure 1;

Figure 3 is a section taken along the line 3—3 of Figure 1;

Figure 4A illustrates relative vertical forces for different ratios of the radii and the lengths of the columnar portion and the auxiliary portion of a vertical buoyancy means for a still water draft of 100 feet;

Figure 4B is similar to Figure 4A and illustrates the selection of the limits of the columnar ratios for the same still water draft of 100 feet;

Figure 5A is similar to Figure 4A except it is for a still water draft of 125 feet;

Figure 5B is similar to Figure 4B except it is for a still water draft of 125 feet;

Figures 6A, 6B and 6C illustrate the variation in mooring force for three types of vertically moored platforms which consist respectively of only one slender, vertical float member; a float member completely submerged; and a buoyancy member of the type used in this invention, Figures 6A and 6B illustrating such variation for prior art structures;

Figure 7A shows the shape of a typical vertical buoyancy means of this invention;

Figure 7B shows the forces acting on a typical vertically moored platform comprising only one vertical float member of the type used in this invention;

Figure 7C is a diagrammatic view for illustrating the relationship of the various volumes of a float member of a floating structure according to the invention;

Figure 8 shows an example of an overturning moment on a floating structure such as shown in Figure 1;

Figure 9 shows an example of the variation in the mooring force for a given leg due to the overturning moments shown in Figure 8;

Figure 10 demonstrates the typical effect on a floating structure according to this invention due to the couple between the net vertical forces on the individual legs;

Figures 11A and 11B illustrate the net variation in mooring force at one leg of a vertically moored platform which comprises vertical float members of a configuration according to this invention;

Figures 12A and 12B illustrate the net variation in mooring force at one leg of a vertically moored platform which comprises vertical float members made up of prismatic cylinders;

Figures 13A and 13B illustrate the net variation in mooring force at one leg of a vertically moored platform in which the float members are made up of deep spheroidal floats only;

Figure 14 shows the maximum variation in mooring force at a given leg, expressed as a percent of the displacement per leg, for various values of the shape parameters r and (L/H) (the terms, r, L and H are defined hereinafter) and for a particular platform size and design condition, as noted;

Figures 15A to 23A illustrate (a) the best combinations of shape parameters r and (L/H) and (b) the range of practical combinations of these parameters for various platform sizes and design conditions, as noted;

Figures 15B to 23B illustrate (a) the best combinations of shape parameters p and r and (b) the range of practical combinations of these parameters for various platform sizes and design conditions, as noted.

Referring to the drawings in which identical numbers are employed to identify identical parts, numeral 10 designates, generally, the floating structure. This includes a deck or platform 12 which may have a derrick 14 mounted thereon. The deck 12 is preferably an enclosed space where living quarters, a workshop area, etc., are located. This is to aid in streamlining the structure. Various auxiliary means, including a port for helicopters, etc., may be provided.

The platform 12 is supported by at least three vertical floats 16. Each includes an upper "skinny" portion 18 and a lower "fat" portion 20. There are enough of these vertical floats 16 to provide stability and there would ordinarily be three or more although there are four shown in Figure 3. The size and location of the lower portions 20 of the floats will be discussed later.

The structure is anchored to the ocean floor. Shown in Figure 1 is a base plate 22. Anchor piles 24 extend into the bottom of the ocean to whatever depth is needed to provide the proper anchorage, e.g., 500 feet. These anchor piles are secured in place, for example by cement 26. Connecting the anchor piles 24 to the floats are a plurality of elongate members 28, alternatively called risers. These elongate members 28 are preferably large diameter steel pipes, e.g., 20 to 30 inches in diameter but could however be cables of wire, chain, or the like. However, it is preferred that they be pipes so that operations can be conducted from the deck down through them to underground formations, for example drilling.

The floating structure is essentially rigid in the vertical direction, but is relatively free to move in the horizontal direction. The restraint experienced against horizontal movement is only due to the horizontal component of the tension in the risers, that component being proportional to the angular departure of the risers from the true vertical. Under the action of wind, current and other steady forces, the platform will be shifted horizontally until the resultant horizontal restraint equals such applied loads. In response to the wave action the platform will oscillate back and forth about its shifted or average position. The platform will, in storm wave situations, generally oscillate horizontally so as to move with the surrounding fluid. The horizontal motion of the platform will basically satisfy the following relationship:—

$$X = A' \frac{H' + B}{H' + M} \cdot \frac{\left[\frac{T_n}{T}\right]^2}{\left[\frac{T_n}{T}\right]^2 - 1} \qquad (1)$$

in which

X=the single amplitude horizontal motion of the platform

A′=the horizontal, single amplitude wave motion of water at the elevation of the centre of buoyancy of the platform. See Equation (2).

B=the buoyancy or displacement of the platform

H′=the "hydrodynamic mass" of water associated with the acceleration of the platform. For most configurations H′ is essentially equal to the buoyancy.

M=the actual weight of the platform

T=the wave period

T_n=the natural sway period, calculated from Equation (3). The water wave motion A′ is calculated, for simple wave motion, according to the following equation.

(2)

$$A' = \frac{h}{2} e^{-2\pi S/\lambda}$$

in which

h=wave height, from crest to trough

S=the submergence of the centre buoyancy of the platform below still water level

λ=wave length ($=5.12T^2$, by the Airy Theory)

The natural sway period of the platform is expressed as

(3)

$$T_n^2 = \frac{L'(H'+M)}{B-M}$$

in which

L′=the length of the risers, and the other symbols are as previously defined.

For most configurations of interest, a wave 100 foot high would cause the platform to move 50 feet either side of the average or shifted position. It is generally to be preferred that the mean position due to the surge motion of the platform during any sea state which develops be approximately equal to the single amplitude of the wave induced motion. For the case just described, an appropriate design shift would be 50 feet. For a water depth requiring vertical risers 1,000 feet long, such a horizontal shift would correspond to a horizontal restraint equal to 1/20th of the tension in the risers. Thus, the tension in the risers should generally be between 15 and 25 times the steady horizontal storm loads. Typically required total tensions of the order of 10,000,000 pounds are to be expected. Typically such a tension could be carried by 16 or 20 pipe risers each of which have a 20 inches outside diameter with a wall thickness of 0.625 inch.

It has been found that when risers such as pipes 28 are under tension and subjected to angular rotation, the effect of the tension is to concentrate the angular rotation at the ends of the pipe. Accordingly, means are provided in the risers 28 to permit this angular rotation with respect to the two terminals of the riser 28. This means comprises a ball joint 30 at the upper end and a ball joint 32 at the lower end of each riser.

An alternative way of providing for the excess stresses which build up near the ends of the risers 28 if they are not jointed would be to provide sections of special size and wall thicknesses at the end of the risers to make them sufficiently strong to withstand the imposed stresses.

The vertical floats 16 are connected by cross bracing 34. This cross bracing is preferably all located below the still water line 36.

As mentioned earlier, the structure will be subjected to various wave forces. In marine engineering, when designing floating structures, or other marine structures for that matter, it is quite common to select what is known as a maximum design wave. The maximum design wave is shown as having a crest 38 and a trough 40.

A particularly desirable shape for the vertically positioned elongate floats is illustrated in Figure 1. With reference to such a shape, the following criteria applies. The buoyancy or displacement volume of the float can be conceived as being made up of two parts. The first part results from the straight, vertical, columnar shape which has the diameter of upper portion 18 and runs the entire vertical length of the float. The volume of this portion of the float comprises between about 40% and about 80%, preferably between 40% and 60%, of the total displacement of the

float. The second or auxiliary volume of displacement is that part which is due to the annular volume between the columnar volume and the inner wall of the enlarged portion 20. This auxiliary volume must be located below trough 40 of the maximum design wave. The float preferably provides a total still water displacement between 15,000,000 and 60,000,000 pounds.

The auxiliary volume should be formed in a smooth and streamlined fashion, as indicated above, as an annular space around the basic cylindrical volume. The size of the auxiliary volume in the annular portion of the "bottle like float" should be reduced to compensate for the displacement provided by that part of the bracing 34 which is below the trough of the design wave. The auxiliary volume provided by the annular space should be streamlined and flared into the basic columnar volume to whatever extent is practical. While the concept is that of columnar volume and an auxiliary volume, it is to be understood that these two volumes can be continuous and that it is not necessary that they be separated into physically distinct compartments.

It is usually necessary that variations in the vertical mooring forces, which arise in response to forces imposed on the structure by wave action, be minimized within the range of wave lengths typically in the range of from about 500 ft. to 2000 ft. Wave action on the structure results in (a) a net vertical force on the structure, (b) a net couple on the structure due to the vertical forces on individual floats, and (c) a net overturning moment on the structure due to horizontal wave forces. All of these forces contribute to the variation in the mooring forces experienced.

The structure minimizes the variation in mooring force by permitting the several contributing forces to offset each other. As stated above, the main contributing forces are: net vertical force, net couple of vertical forces and net overturning moment. If a structure according to the invention were not used, one of these forces might be overpowering. For example, if the vertical forces on the individual bottle-like-floats, were due to the design of the floats eliminated or minimized, thereby eliminating or minimizing the net vertical forces and the net couple due to the vertical forces on the structure, the variations in mooring force would be due entirely to the overturning moment and could be undesirably large, especially for the longer wave lengths. On the other hand, if the buoyancy arrangement were such that a small net vertical force were experienced at all wave lengths, then a phenomenon associated with these forces the net couple due to the vertical forces, would cause a net reduction in the overturning moments experienced at the larger wave lengths. Therefore, a careful selection of buoyancy distribution can result in a minimization of the variations in mooring force experienced over the entire range of important wave lengths.

The vertical forces on the structure are dominated by forces which fall into two categories: namely, (a) those due to variable buoyancy and (b) vertical water acceleration forces. While there are other contributions to the next vertical forces experienced they are of lesser importance. All of these forces on the structure can be calculated by elementary, commonly understood means. The dominant two forces may be combined for calculation purposes into one net force, heave, which is discussed below. The two categories of dominant vertical forces act in opposite direction to one another and one of the aims is to carefully adjust the magnitudes of these forces to obtain desired net vertical forces. This is possible with this design for certain ratios

$$\left(\frac{L}{H}\right)$$

of the length (L) of the enlarged portion to the total design draft (H) and for certain ratios (r) of the radius R_1 of the enlarged portion to the radius R_0 of the cylindrical portion for a selected draft. L, H, R_0 and R_1 are shown in Figure 1. The ratio "p" is defined as the ratio of the displacement of the columnar portion to the total displacement.

The net vertical forces on the structure will first be considered. The net overturning moment and how the design of the structure can minimize such moment will be considered later. The various net vertical forces experienced can be calculated by using the following equation.

(4)

$$F(\eta, 0) = \Delta(\eta) - \Delta(0) - k\rho g \eta \int_{y=0}^{\eta+H} A(y)\, \varphi(y)\, e^{k(y-H)} dy$$

where:

F=net change in vertical force, positive upwards

$\Delta(\eta)$=total displacement below the instantaneous water level

$\Delta(0)$=design displacement, or total displacement below design still water level

k=wave decay factor, i.e., $=\frac{2\pi}{\lambda}$ where λ=wave length (Airy Theory)

ρ=water mass density

g=gravitational acceleration

A(y)=horizontal cross-section area of vertical buoyancy members (varies with depth or y)

$\varphi(y)$=hydrodynamic mass coefficient and varies with depth,

$$\text{i.e., } \varphi(y)=\frac{\text{mass of cylinder+added fluid mass}}{\text{mass of cylinder}}$$

H=design draft

y=a vertical coordinate position measured upwards from the base of the buoyancy means

η=a vertical coordinate position measured upwards from the design still water level to the instantaneous water surface (=y−H)

In equation (4) terms $[\Delta(\eta)-\Delta(0)]$ give the force due to the variable buoyancy, and the remaining term gives the force due to the vertical water acceleration.

Consider first two very elementary types of vertically moored structures as are shown in Figures 6A and 6B. Figure 6A shows a buoy consisting of one cylinder. This buoy is moored by one or more vertical tethers such that it is not free to move vertically, but it can move horizontally or rotate. The buoy does not have an annular or auxiliary portion. Therefore, the ratio p which is defined as the ratio of the displacement of the columnar portion to the total displacement, equals one (p=1). The three curves in Figure 6A show the variation in the net vertical forces on the cylinder due to the passage of a single wave from three different wave trains. The three wave trains have periods of 10-, 14- and 20-seconds; the corresponding wave lengths being 512-, 1004- and 2048-ft, respectively. In this example and all subsequent examples it is assumed that the wave height corresponding to each wave length equals either one-tenth of the wave length or the maximum design wave height, whichever is smaller. In this and most of the subsequent examples, except where noted, the maximum design wave height is 100 ft. Therefore, the corresponding wave height is 100 ft. Therefore, the corresponding wave heights for the curves in Figures 6A are 51.2-, 100- and 100-ft., respectively. The variation of net vertical forces is expressed as a percentage of the total displacement. For example, a 20-second wave causes a reduction in the net vertical force of about 32 percent of the displacement when the wave trough is aligned with the axis of the cylinder buoy. When the crest is aligned with the axis of the cylindrical buoy there is an increase in the net vertical force of about 22% of the displacement. By virtue of the decrease in the net vertical force at the trough and the increase at the crest, this example demonstrates that forces due to the variable buoyancy are dominant for a high ratio p. As an explanation of the terminology used the term "leading crest" is that part of the wave half way between the trough and the next crest. The term "following crest" is that part of the wave train at a point one-half way between the crest and the next trough.

Figure 6B shows similar curves for another configuration of a vertically moored buoy. In this case the entire displacement is created by a spherical cavity at the bottom of the buoy as the portion of the buoy projecting upwards from the sphere has an extremely small cross-section. Consequently, the cylindrical portion contributes virtually nothing to the total displacement, and the annular, or auxiliary, portion provides the entire displacement. The ratio p equals zero. The curves of Figure 6B show that the maximum variation in net vertical force is about 30 percent of the displacement in the long period, 20-second wave. However, in this example the buoy experiences an increase in the net vertical force when the wave trough is aligned with the buoy, rather than a decrease as with the cylindrical buoy in Figure 6A. This example demonstrates that for a low ratio p the forces due to vertical water acceleration are dominant.

For a low ratio p, the forces due to vertical water acceleration are dominant

while for a high ratio, forces due to variation in the buoyancy are dominant. Moreover, for an intermediate value of the ratio, there exists a balance between the variable buoyancy forces and the vertical water acceleration forces such that the variations in net vertical forces for the wave lengths of interest are substantially smaller than in the two extreme cases examined above.

Consider for example a vertically moored bottle-like structure of the type shown in Figure 6C. In this case the parameters describing the physical properties of the structure are r=1.853,

$$\left(\frac{L}{H}\right)=0.5$$

and $p=0.545$. In addition, the maximum design wave height, h_{max}, is 100 ft. and the draft, H is 125 ft., which is the same as in the two preceding examples. The curves of Figure 6C show the variation of the net vertical forces when the structure is subjected to the same three waves. In this case the maximum variation in force is about 7 percent of the displacement and it occurs under the influence of both the 10- and 20-second waves, although it is an increase in the case of the 10-second wave when the wave trough is aligned with the structure and a decrease for the 20-second wave. Figure 6C shows that for a bottle-shaped structure the distribution of displacement described above vertical water acceleration forces dominate for short period waves while variable buoyancy forces dominate for longer period waves. Furthermore, there is a wave (about a 16-second period wave) for which there is virtually no variation in the net vertical forces experienced because there is a perfect balance between the variable buoyancy and vertical water acceleration forces.

If the ratio p had been slightly greater, buoyancy forces would have dominated as in Figure 6A; consequently the maximum variation due to the 20-second wave (a decrease in the net vertical forces) would have been greater than 7 percent. If the ratio had been smaller, as in Figure 6B, vertical water acceleration forces would have dominated and consequently the maximum variation due to the 10-second wave (an increase in the net vertical forces) would have been greater than 7 percent. Therefore, for the range of waves of interest, 10- to 20-second waves, a best balance between the two influencing vertical forces is obtained for the combination of parameters shown in Figure 6C, $r=1.853$, $L/H=0.5$ and $p=0.545$.

There are also other combinations of the parameters r, L/H and p for which a best balance between the two types of vertical force may be obtained. These are found by studying a wide range of practical combinations of the parameters in the same manner as has been described for Figure 6C. For each set of parameters the maximum variation in the net vertical force due to any wave in the range of interest is noted. The maximum variation is then plotted for each set of parameters on a type of "contour" plot such as is shown in Figures 4A, 4B, 5A and 5B. Such a plot indicates the combination of parameters giving the lowest value for the maximum variation, the "valleys", and also shows which set of parameters give slightly higher, but practically acceptable values of the variation. Figures 4A and 4B give values for a structure having a 100 ft. draft and Figures 5A and 5B for one with a 125-ft. draft.

The basic configuration of the bottle-shaped structure is described by any two of the three parameters. The most fundamental set is r and L/H since p is a function of these two parameters. On the other hand, it is convenient to express the design of the floats in terms of p and r. Therefore, both combinations of parameters are used in Figures 4A to 5B to illustrate the preferred design configurations. In Figure 4A, solid line 80 represents the relation between r and

$$\frac{L}{H}$$

for which the magnitude of the net vertical force experienced is minimized over the selected range of wave lengths. The same relationship is illustrated by solid line 80A of Figure 5A. These forces are evaluated using equation (4).

It is recognized that the most practical selection of r and

$$\frac{L}{H}$$

may not always be those which produce minimum net vertical forces and therefore some knowledge is needed of the influence of variations from the values producing the minimum. Area 82 on either side of line 80, Figure 4A, (or area 82A of Figure 5A) represents variations in r and

$$\frac{L}{H}$$

which might occur or be possible if a net vertical force equal to 10% of the total displacement could be tolerated. If a net vertical force equivalent to 12-1/2% of the total displacement could be tolerated, r and

$$\frac{L}{H}$$

could vary so long as their corresponding ordinate and coordinate intersect within shaded area 84 in Figure 4A.

In Figure 4B, the solid line 90 represents the best selection of p and r for a design draft of 100 feet, i.e., the magnitude of the net vertical forces experienced will be minimized over the selected range of wave lengths for the values of p and r falling on solid line 90. (In Figure 5B, solid line 90A represents the best selection of p and r for a design draft of 125 feet.) In Figure 4B, shaded area 92 and shaded area 94, respectively represent regions for which the force changes are less than 10% and 12-1/2% of the total displacement. In Figure 5B, shaded area 92A represents regions for which the force changes are less than 10% of the total displacement for a structure of 125 feet draft.

Figures 4A and 4B, illustrate that for the design of a vertically moored structure consisting of a single bottle-shaped structure having a draft of 100 ft., the maximum variation of net vertical force on the structure could be minimized by keeping the displacement due to the columnar portion between 40 and 60 percent of the total displacement ($0.4 \leq p \leq 0.6$). More specifically, a more practical design, one for which the maximum variation of the net vertical force experienced is within 12.5 percent of the total displacement, could be obtained by selecting combinations of design parameters which fall within the shaded region 84 of Figure 4A or 94 of Figure 4B; or one for which the maximum variation of the net vertical force is within 10 percent of the displacement could be obtained by a selected combination of design parameters which lie within the shaded region, 82 of Figure 4A or 92 of Figure 4B. Furthermore, if the combination of design parameters should lie on the heavy line, 80 in Figure 4A or 90 in Figure 4B, then the maximum variation of net vertical force would be reduced to the smallest amount possible.

Figures 5A and 5B, illustrate that for the design of a vertically moored structure of this nature having a draft of 125 feet, the maximum variation of the net vertical force on the structure could be minimized by keeping the displacement due to the cylindrical portion between 45 and 65 percent of the total displacement ($0.45 \leq p \leq 0.65$). More specifically a more practical design for a vertically moored structure for which the maximum variation of net vertical force experienced is to be within 10 percent of the total displacement could be obtained by selecting combinations of the design parameters which fall within the shaded region of Figures 5A and 5B. Furthermore, if the combination of design parameters should lie on the heavy line in Figure 5A or 5B, then the maximum variation of the net vertical force would be reduced to the smallest amount possible.

The configuration of a typical bottle-shaped float is illustrated in Figure 7A, in which the basic design parameters L, H, R_0 and R_1 are defined. It is best to maintain the annular or auxiliary displacement as low on the bottle configuration as possible; in this way the annular or auxiliary displacement is maintained below the wave trough 40. The variation in the net vertical force experienced would rise sharply if the annular portion of the displacement should enter into the wave trough. The height of the annular or auxiliary displacement is measured from the lowermost

point CK on the bottle-shaped float. Consequently, a most advantageous design is one for which

(5)

$$L \leq H - h_{max}/2$$

(6)

$$(L/H) \leq 1 - 1/2\ (h_{max}/H).$$

Figure 7A also shows the approximate location of the centre of gravity CG and the center of buoyancy CB of a typical bottle configuration. The centre of gravity of a vertically moored platform is generally higher than the centre of buoyancy due to the large mass of the structure, such as the bottle extension or deck, and allied equipment located well above the design wave crest. Such a structure would normally be unstable if it were not for the vertical tethering force T which is usually applied near the base of the structure, for example at point CK.

This simple type of vertically moored structure consisting of a single bottle-shaped float is restrained from vertical motion, but is free to move horizontally and moreover, is subjected to roll or pitch motions. When subjected to the horizontal component of oscillatory wave forces, the platform moves back and forth through the water. Figure 7B shows the bottle-shaped float at its furthermost excursion towards the right; at this instant the structure is motionless and its acceleration is at a maximum towards the left. At this instant the horizontal forces shown are in equilibrium. The governing horizontal forces are (a) the fictitious force Fp due to the platform acceleration which has a point of application at the centre of gravity, (b) the horizontal water particle acceleration (or inertia) forces F_w which has a point of application in the vicinity of the centre of buoyancy CB, and (c) finally the horizontal component T_H of the tethering force which acts at the point CK. The above mentioned forces can be calculated from fundamental textbook dynamic and hydrodynamic theories. While these forces are in equilibrium as horizontal force, they produce moments which are not themselves in equilibrium. These moments will hereinafter be called "overturning moments". Relative water particle motion also produces drag forces with horizontal components and associated overturning moments but due to the shape of the bottle, these are negligible.

In the case of the simple vertically moored platform, consisting of a single bottle-shaped structure the overturning moments cause the structure to pitch through an angle θ, which is the single amplitude degree of pitch motion. The degree of pitch is large enough for the couple between the static vertical forces to be sufficient to counter balance the overturning moments. The static vertical forces consist of (a) the vertical component Tv of the tethering force (b) the buoyancy force B and (c) the weight of the platform M.

Fig. 7c shows diagrammatically the relationship of the various volumes of the float members. The first volume VI is below the still water line and above the trough 40 of an expected maximum wave. This first volume V1 has a cross-sectional area obtained by dividing the volume V1 by the depth of the trough 40. The second volume V2 is positioned below the trough 40 and is composed of a third volume V3 and a fourth volume V4 with the third volume V3 being equal to the vertical dimension of the float member below the trough multiplied by its cross-sectional area. The fourth volume V4 is equal to the second volume V2 minus the third volume V3 and constitutes between about 20% to 60% of the total displacement of the float member. The configurations of the float members can be varied, however, from the particular configurations illustrated in the drawings inasmuch as it is the relationship of the various volumes which is critical.

Returning now to the floating structure shown in Figures 1 to 3 it is recalled that the platform is free to move in a horizontal direction only and pitch or roll motions as well as vertical motions are restrained. The platform is subjected to the same forces and overturning moments as were the individual bottle-shaped structures just discussed: the vertical and horizontal water particle acceleration forces, variable buoyancy forces, and platform inertia.

The dynamic vertical forces are primarily the variable buoyancy and vertical water acceleration forces as before. There is also a vertical drag force, but this is insignificant compared to the first two. The net resultant of these vertical forces is countered by variations in the tethering forces, which is the same as occurs in the case of single vertically moored bottle-shaped structure. Also as with the single bottle-shaped structure, the horizontal forces experienced such as the platform inertia and

the horizontal water inertia forces are countered by the horizontal component of the tethering force. However, because this more complex vertically moored platform is not free to undergo pitch or roll motion, the overturning moments must be countered by an additional variation in the tethering force. The overturning moment for a multi-float vertically moored platform is still mainly due to the couple developed between the horizontal forces such as those due to (a) the platform inertia, (b) horizontal water particle acceleration forces, and (c) the horizontal component of the tethering force. There are other, less significant sources of an overturning moment and these are shown in Figure 8 for a 100-ft., 20-second wave acting on a structure. As noted previously the horizontal drag produces a small and insignificant contribution to the overturning moment. Vertical water particle drag forces, due to the phase difference of the wave cycle at the different floats, also contribute a small amount of overturning moment. Wind lift on the deck may produce a small amount of moment. Where elongate members, such as risers, are used to tether the platform rather than cables and if the ends of these members are rigidly attached to the platform rather than attached by a jointed connection such as a ball joint, then there is produced a significant riser end moment which adds to the overturning moment on a platform. The dashed line in Figure 8 shows the net overturning moment on a typical 4-float, vertically moored platform due to a 100-foot high, 20-second period wave. The net overturning moment is not radically different from the overturning moment due only to the couple produced by the horizontal forces.

Using simple textbook statics, the variation in the net tethering force due to the overturning moment experienced can be calculated by making the most reasonable assumption that the platform is very rigid compared to its vertical tethers which act like elastic springs. For a four-float platform, the overturning moment experienced is most demanding on the tethers at any given float if the storm, or waves, approach the platform along a diagonal rather than a direction normal to a side. In this case the tethers at the two diagonally opposite floats which are in line with the storm direction provide the entire reaction to the overturning moment. If the centre-to-centre float) spacing along a side is "A", then the reaction to the overturning moment in each resisting float is the value of the overturning moment divided by $A\sqrt{2}$. The tethering forces in the other two floats are not affected by this overturning moment.

Considering the influence of static horizontal forces such as wind and current on the variation of the vertical tethering forces, one of the two floats resisting the overturning moment will be more heavily loaded than the other. This float, which will hereinafter be called Float No. 4 as indicated in Figure 11A, is that float which is oriented toward the oncoming waves. While the influence of static horizontal forces will not be considered here, it is convenient to distinguish this float from the others. For a positive overturning moment as shown in Figure 8, the variation in the tethering force at Float No. 4 to counter this is positive as shown in Figure 9, for each of three different waves. Figure 9 shows the variation in the tethering force in Float No. 4 due to the overturning moment only. The variation is expressed as a percentage of the displacement per float; in this case it is a percentage of one-fourth of the total displacement.

In a floating structure such as here described, the floats may be spaced 200 feet apart, more or less. Because of the wide spacing, each of the floats may experience different net vertical forces at any given instant. Consequently, it is impossible for all of the floats to simultaneously experience the maximum net vertical force due to long period waves. Therefore, the next vertical force on the entire four-float structure will never be as great as four times the net vertical force on a single vertically moored mottle-shaped float, and in turn, the reaction in the risers at each float due to net vertical force only will never be as great as the reaction in the risers of a single float.

Furthermore, because of the wide float spacing the differences in net vertical forces on the individual floats at any instant will give rise to couples which must also be countered by variations in the tethering forces. Consider the example depicted in Figure 10, where the four floats are spaced 200 feet apart in the outline of a square and a wave with a 400-foot wave length is passing the platform. There is an instant when the crest of the wave is aligned with two floats and the trough is aligned with the other two. If on the structure the variable buoyancy forces are governing for this wave, then the net vertical forces on the floats at the crest are upwards and at the trough are downwards, as illustrated by the arrows in Figure 10. While the net vertical force on the entire structure may be nearly balanced, there is a relatively large couple, or moment, acting on the structure due to the differences in the net vertical

force. This couple must be countered by variations in the tethering forces in the same manner as for the overturning moments.

It can be shown that if the variable buoyancy contribution to net vertical force is greater than that due to the vertical water particle acceleration, such as with long period waves, then this coupling of net vertical forces acts in the opposite sense to the dominant source of the overturning moment mentioned previously. Consequently, the couple due to the net vertical force on each float tends to reduce the influence of the overturning moment, especially for long period waves. However, as the net vertical force on the individual floats is increased in order to reduce the effect of the overturning moment, the net vertical force on the entire structure is increased. In other words, although the variation in tethering force is decreased through a reduction of the effect of overturning moment, it is at the same time increased due to the increase of the net vertical force on the platform. There exists a proper value of the net vertical force on the individual floats for which the net effect of these influences is minimized. It is important to minimize the variation in tethering force on the most heavily loaded float, and therefore the maximum mooring force necessary over the range of important wave lengths, through a proper selection of the ratios of variable bouyancy force and vertical water acceleration force experienced as was done previously to minimize the net vertical force acting on a single vertically moored bottle-shaped float.

There are three contributions to the variations in tethering force experienced in the most heavily loaded float. These are (a) the reaction to net vertical force on the entire structure, (b) the reaction to the overturning moments and (c) the reaction to couple due to the vertical forces on the individual, widely spaced floats. Figure 11A shows the variations in the tethering force in Float No. 4 due to each of these influences for a 100-ft., 20-second wave. The net variation is also shown by the heavy line. For this example the platform has four bottle-shaped floats where each has the same physical properties as that in Figure 6C: $r=1.853$,

$$\frac{L}{H}=0.5,$$

$p=0.545$. The variation in tethering force is expressed as a percentage of the displacement per float. The maximum variation for the 20-second wave is about 13.5 percent and occurs shortly after the wave trough has passed the centre of the platform. In Figure 11A it is worth pointing out that for the long period wave, the variation due to the couple due to the net vertical forces on the individual floats while small in magnitude acts opposite in sense to the variation due to the overturning moments.

Figure 11B shows the net variation in tethering force for three different waves. It is evident from these curves that the maximum variation in the force due to any of the waves in the range of interest is 14.1 percent. For the platform examined in Figure 11, the draft is 125 feet, the float spacing is 160 feet, total displacement is 28,675 kips (1 kip=1000 pounds), the weight of the structure and its equipment is about 18,675 kips and the total, still water mooring force is 10,000 kips. While the maximum net variation in the mooring force is only 14.1 percent of the displacement per float, it is about 40 percent ($14.1\times28{,}675/10{,}000=40.4$) of the still water mooring force per float.

Figures 12 and 13 show the influence of other float configurations on maximum net variations in the tethering force experienced. In each of these examples the platform size including its displacement is the same as in Figure 11 and only the proportions of the columnar and annular displacements are altered by varying the shape of the individual floats. The variation in the mooring force due to the overturning moment is essentially the same in each case for similar waves. Therefore, the net variation in the mooring force is altered only by the variation of the net vertical forces on the individual floats.

In Figures 12A and 12B the displacement is due entirely to the cylindrical portion ($p=1$). It is interesting to note that the variation due to the couple produced by the net vertical forces on the individual floats almost completely counter-balances the variation due to the overturning moment. Consequently, the net variation in mooring force is almost entirely due to the variation in the total net vertical force on the platform. As a result, the maximum variation in the mooring force is 32 percent of the displacement per float and occurs when the trough of the wave is at the centre of the

platform. This is very similar to the response of the vertically moored, single cylindrical float.

In Figures 13A and 13B the displacement is due virtually entirely to the annular portion at the base of the float ($p=0$). In this case the net variation of the mooring force is a complex combination of the three influences shown in Figure 13A for the 20-second wave. Because the vertical water acceleration forces are dominant instead of variable buoyancy forces, the forces derived from the net vertical force on the individual floats act in the opposite sense from Figure 12A. Consequently, the variation in the mooring force due to the couple of the net vertical forces on the individual floats adds to the variation in mooring force due to the overturning moment. Furthermore, the maximum net variation in the mooring force, 45 percent, is much greater than the net vertical force on a single float of this configuration.

It is apparent by comparing Figure 11B with Figures 12B and 13B that the maximum variation in the mooring forces, for the range of waves in interest, can vary significantly depending on the configuration of the individual floats. There are certain combinations of the design parameters r, L/H and p for which a minimum value can be achieved of the maximum variation in mooring force experienced. A type of "contour" plot, similar to those prepared for the net vertical forces on the individual floats in Figures 4 and 5, can be prepared giving the percentages variation in the mooring force as a function of the shape parameters r, L/H and p.

In order to prepare such a plot there is a need to examine a large number of examples such as those of Figures 11, 12 and 13 for the range of waves of interest and for a wide range of the shape parameters. For each set of shape parameters the maximum variation of the mooring force is noted. Next, the values of the maximum variation can be plotted as a function of the shape parameters such as is done in Figure 14 or 15. Actually, Figure 14 assists in the preparing of Figure 15. In Figure 14 the maximum variation (designated ΔT), as a percentage of the displacement per float (designated b), is plotted versus r for fixed values of L/H. This simplifies the procedure for determining the values of r and L/H at which the maximum variation is an even value, such as 0.14, 0.16, 0.18, 0.20, etc. Finally, the contours for the fixed values of the maximum variation are plotted versus L/H and r as in Figure 15A, or versus p and r as in Figure 15B. Figures 14, 15A and 15B have been prepared from calculations for a specific platform. The pertinent data are

1) Maximum Design Wave Height=100 feet,
2) Platform Draft=125 feet,
3) Float Spacing=160 feet,
4) Total Displacement=28,675 kips,
5) Platform Weight=18,675 kips,
6) Total Still Water Mooring Force=10,000 kips.

From Figure 14 it is apparent that the minimum attainable value of the maximum variation is about 13.5 percent of the displacement per float (28,675/4=7170 kips). This would account for about a 39 percent variation in the still water mooring force per float (13.5×28,675/10,000=38.7). It may not always be practical to select a configuration for which the shape parameters produce the lowest value of the maximum variation. However, a practical range of maximum variations, e.g., less than 1.2 times the lowest value, is attainable if the set of shape parameters lie within the 16 percent contours (1.2×13.5=16.2), i.e. the shaded regions of Figure 15A or 15B.

When designing a platform for the size and maximum design wave height listed above, the maximum variation of mooring force for the range of wave lengths of practical interest can be minimized to a range of practically acceptable values (e.g., having an upper limit less than 16 percent) if the shape parameters which govern the shape of the individual floats lie within the shaded regions of Figure 15A or 15B. Moreover, the best selection of shape parameters in order to minimize the variation in the mooring forces are those falling on the heavy dashed line in either Figure 15A or 15B.

Figure 15 illustrates the best selection of shape parameters for a limited case, namely one designed for a maximum wave, draft, displacement, etc., equal to the values itemized above. The best selection of shape parameters for other values of float spacing, draft, maximum design wave height, displacement and platform weight will now be demonstrated.

Comparison of Figures 16, 15 and 17, in that order, demonstrates the effect of varying the float spacing. In these examples all other parameters remain constant,

while the float spacing takes values of 140 feet, 160 feet and 200 feet, respectively. Changing this spacing does not significantly after the position of the heavy dashed line which describes the best selection of shape parameters. Neither does it significantly alter the region for selection of the most practical combinations of shape parameters, the shaded region in each figure. (In these examples and all subsequent examples, the shaded region bounds those sets of parameters for which the maximum variation is less than or equal to 1.2 times the lowest attainable value of the maximum variation). However, for the range of values of spacing examined, the minimum attainable value of the maximum variation is approximately proportional to the inverse of the float spacing.

Comparison of Figures 18, 15 and 19 in that order demonstrate the effect of altering the platform draft. In these three examples all parameters are the same as those listed above except the still water draft of the floats, which are 100 feet, 125 feet, and 150 feet, respectively. Changing the draft does alter slightly the position of the heavy dashed line and shaded region, which denote the best combination of shape parameters and the range of practical combinations of the shape parameters, respectively.

As one example, for a platform with the following properties:

1. Maximum Design Wave Height=100 feet
2. Total Displacement=28,675 kips
3. Platform Weight=18,675 kips
4. Total Still Water Mooring Force=10,000 kips

and for a 100-foot draft, the most practical combination of shape parameters are those falling in the shaded region of Figures 18A and 18B and the best selection of shape parameters are those lying on or near the heavy dashed line in Figures 18A and 18B. Also for a platform with the above list of properties, but a draft of 150 feet, the most practical combination of shape parameters are those lying in the shaded region of Figure 19 and the best selection of shape parameters are those sets lying on or near the heavy, dashed line of Figure 19. Furthermore, for a platform with the properties listed above and designed for a maximum design wave height listed above but having a draft between 100 feet and 150 feet, the range of the most practical sets of the shape parameters are found approximately by interpolating between the shaded regions of Figures 18, 15 and 19; and the best combination of shape parameters are determined approximately by interpolating between the heavy dashed lines in Figures 18, 15 and 19. For these figures the maximum value of the ratio p is about 0.8 and the minimum value is about 0.5. However, in Figure 4 the minimum value of p is about 0.4. For a wide range of design in vertically moored platforms (covering the generally acceptable sizes) the ratio should be between about 0.4 and 0.8.

Furthermore, the lowest attainable value of maximum variation is influenced significantly by changes in draft, especially for shallower drafts. The lowest value is about 15 percent for a 100-foot draft as compared to 13.5 percent for a 125-foot draft and about 13.2 percent for a 150-foot draft. For a decrease in draft less than 100 feet, the lowest value of the maximum variation rises rapidly, while for an increase in draft above 150 feet there is little additional reduction in the lowest value of the maximum variation. Therefore, at least for a maximum design wave height h_{max} of 100 feet, the penalty in terms of the variation of the tethering force experienced becomes very severe for a draft H less than 100 feet

$$\left(\frac{h_{max}}{H} > 1.00\right).$$

Furthermore, for the same maximum design wave height h_{max}, the penalty in terms of the provision of unnecessary structural parts becomes costly with a design draft H greater than 150 feet

$$\left(\frac{h_{max}}{H} < 0.67\right).$$

Therefore, for a platform of a displacement of 28,675 kips, the most attractive ratio (h_{max}/H) of the maximum design wave height to the draft is about 0.8 and the practical range for this ratio is between 0.67 and 1.00 ($0.67 \leq h_{max}/H \leq 1.0$).

In Figure 18, the sharp convergence of the "contours" for values of L/H greater than 0.5 demonstrates the effect of the annular portion of the displacement projecting above the wave trough. The result is that the values of the maximum variation in the mooring force rise sharply as more of the annular displacement projects into the trough of the wave. Therefore, the best selection of shape parameters is one which maintains the top of the annular, or auxiliary, portion of the displacement below the trough of the maximum design wave. Mathematically, this is formulated by the bounds established by the inequalities (5) or (6).

The best selection of the draft for a given maximum design wave height should be determined from the ratio ($h_{max}/H \cong 0.8$, but it is also instructive to look at the effect of varying the draft at constant values of this ratio. Figures 20 and 21 demonstate the values of the maximum variation of the mooring force for other maximum design waves, of 60 feet and 80 feet, and corresponding structure draft, or 75 feet and 100 feet, respectively. In each case the float spacing displacement and platform mass is the same as in Figure 15. Also, the ratio of the maximum design wave height to the draft is the same in every case ($h_{max}/H=0.8$).

Comparison of Figures 20, 21, and 15 shows the effect of varying the draft for fixed ratios of (h_{max}/H). The effect of using a smaller draft is to alter the position of the heavy, dashed line and the shaded region, which correspond to the best combination of shape parameters and the most practical range of shape parameters, respectively. More importantly such a comparison shows that the lowest attainable value of the maximum variation in the mooring force is not altered significantly by so large a variation in the draft; in the three examples given the value is about 12.1 to 13.5 percent. Therefore, the best ratio of the maximum design wave height to the draft is about 0.8 ($h_{max}/H \cong 0.8$), independently of the value of either the draft or the maximum design wave height. However, the density of the lines in Figure 20 indicates for so small a draft (or more exactly, for so large a displacement for the given draft) that the values of the maximum variation in the mooring force are very sensitive to the selection of the shape parameters.

As an example, for a platform with the following properties:

1. Ratio: $h_{max}/H=0.8$
2. Total Displacement=28,675 kips
3. Platform Mass=18,675 kips
4. Total Still Water Mooring Force=10,000 kips

and for a 75-foot draft, the most practical combination of shape parameters are those falling in the shaded region of Figure 20 and the best selection of shape parameters are those lying on the heavy, dashed line in Figure 20. Also, for a platform with the above listed properties, but a draft of 100 feet, the most practical combination of shape parameters are those falling into the shaded region of Figure 21 and the best selection of shape parameters are those sets lying on the heavy, dashed line of Figure 21. Furthermore, for a platform with the dimensions listed above and for drafts lying between 75 feet and 125 feet, the range of most practical combinations of the shape parameters are found approximately by interpolating between the shaded regions of Figures 20, 21 and 15; and the best combination of shape parameters are determined approximately by interpolating between the heavy, dashed lines in Figures 20, 21 and 15.

Comparison of Figures 22, 15 and 23, in that order, demonstrates the effect of the total displacement on the maximum variation of mooring force. For each case shown the maximum design wave height is 100 feet, the draft is 125 feet and the float spacing is 160 feet. The total displacements are 14,700 kips, 28,675 kips and 57,350 kips, respectively. The ratio (M/B) of the platform mass to the total displacement is the same in each case. Consequently, two parameters have been varied simultaneously; however, as will be discussed shortly, variation of the platform mass within practical limitations has no significant influence on the values of the maximum variation of the mooring force. Since the total still water mooring force T is simply the difference between the total displacement and platform mass, the ratio (T/B) is also the same in each example. Therefore, in order to express the variation of mooring force as a percent of the still water mooring force, the value of the variation found in the "contour" plots, which is expressed as a percent of the displacement per leg, is multiplied by 2.87 (=28,675/10,000) in each of these examples.

As seen by the comparison, changing the displacement has a significant influence on the selection of the proper shape parameters. Moreover, the lowest attainable value of the maximum variation rises with a decrease in the displacement whereas

this value does not decrease significantly for an increase in displacement. From an examination of several other examples not shown here, it was found that the values of the maximum variation rise sharply for displacements less than about 20,000 kips in the case of the specific design properties listed above.

Therefore, for a platform with the following design parameters and dimensions:

1. Ratio: $h_{max}/H=0.8$
2. Draft=125 feet
3. Ratio: $M/B=18{,}675/28{,}675$
4. Ratio: $T/B=10{,}000/28{,}675$

and for a 14,700-kip displacement, the most practical combination of shape parameters are those falling in the shaded region of Figure 22 and the best selection of shape parameters are those lying on the heavy, dashed line in Figure 22. Also, for a platform with the above listed properties, but a 57,300-kips displacement, the most practical combination of shape parameters are those falling into the shaded region of Figure 23 and the best selection of shape parameters are those sets lying on the heavy, dashed line of Figure 23. Furthermore, for a platform with the design properties listed above and for displacements lying between 14,700 kips and 57,300 kips, the range of most practical combinations of the shape parameters are found approximately by interpolating between the shaded regions of Figures 22, 15 and 23; and the best combinations of shape parameters are determined approximately by interpolating between the heavy, dashed lines in Figures 22, 15 and 23.

Several cases, not included herein, have been examined in which the platform mass was varied independently of all other parameters. It was observed that such variation of the platform mass, within practical limitations, did not significantly alter the range of the most practical combinations of shape parameters in each case, the shaded regions, or the values of the best combination of shape parameters in each case, the heavy, dashed line.

The practical range of the platform mass was determined as follows. The platform mass comprises (a) equipment of weight Q such as for drilling or producing and (b) the structural mass of the platform. The mass of the deck required to provide the necessary support for the equipment of weight Q is approximately Q/4. Also, the mass of the jacket necessary to obtain the required displacement B is approximately B/4. These two values are sufficiently accurate for a practical range of platform dimensions. Therefore, the total platform mass is the sum of the above three contributions, or

(7)
$$M=Q+Q/4+B/4=(5Q+B)/4$$

For the purposes of offshore petroleum drilling and production, the equipment weights might vary between 4500 kips and 18,000 kips. Therefore, the bounds on the platform mass are a function of the design displacement as follows:

(8)
$$5600 \text{ kips}+B/4\leq M\leq 22{,}500 \text{ kips}+B/4$$

Therefore, for the range of values for displacement ($14{,}700 \text{ kips}\leq B\leq 57{,}300 \text{ kips}$), the practical values of platform mass are bounded by the above inequality.

In view of the above description of the practical range for the platform mass, the maximum net variation of the mooring force, where expressed as a function of the displacement per float, is not significantly influenced by an alteration of the platform mass. However, the maximum variation of the mooring force expressed as a percentage of the total mooring force can be decreased by decreasing the platform mass, and consequnently, increasing the total mooring force, for a fixed displacement, as is demonstrated by the following derivation:

(9)
$$\frac{\Delta T}{T}=\left(\frac{\Delta T}{B}\right)\cdot\frac{B}{T}=\left(\frac{\Delta T}{B}\right)\cdot\frac{B}{B-M}=\left(\frac{\Delta T}{B}\right)/\left(1-\frac{M}{B}\right)$$

While the best selection of shape parameters has been described for only a few of the many examples studied, a means for determining the best selection of shape

parameters for the entire range of each of the parameters will now be described. Many examples, not all of which have been included herein, have been studied. These examples were selected from the large range of cases bounded by the limits on the following parameters:

1) Maximum design wave height, 60 ft. $\leq h_{max} \leq$ 100 ft.
2) Draft, 75 ft. $\leq H \leq$ 150 ft.
3) Float Spacing, 140 ft. $\leq A \leq$ 200 ft.
4) Displacement, 14,700 kips $\leq B \leq$ 57,300 kips
5) Platform Mass, see (8) for limits on M
6) Total mooring force, T=B−M

Obviously, not all of the possible combinations of these parameters could be examined. However, a sufficient number of examples were studied so that an empirical formulation could be derived, using curve fitting techniques, which will give with suitable approximation the best selection of the shape parameters.

Best Combinations of Shape Parameters — Those combinations of shape parameters which give the lowest value of the maximum variations of the mooring force (those combinations which were defined by the heavy, dashed lines in Figures 15 to 23) are defined by the formula

(10)
$$r_{bt} = 1 + [C/(L/H)]^n$$

where

(11)
$$C = (0.4505) - \frac{(29.775')}{H} + \left(\frac{h_{max}}{H}\right)\left[\frac{(4588^k)}{B} - (0.07)\right] + \left(\frac{h_{max}}{H}\right)\left[(0.05) - \frac{B}{(573{,}000^k)}\right]$$

(12)
$$n = -(0.088) + \frac{H}{(125')}\left[1 - (0.561)\left(\frac{h_{max}}{H}\right)\right] + \frac{(3928.5^k)}{B}$$

Formula (10) is valid for

(13)
$$\left(\frac{L}{H}\right) \leq 1 - \tfrac{1}{2}\left(\frac{h_{max}}{H}\right) \text{ and}$$

gives the best value of r for each value of L as a function of the draft H, displacement B and the ratio (h_{max}/H) of the maximum design wave height to the draft. The best value of r for each L is independent of the float spacing A and platform mass M as was taught earlier.

Range of Practical Values — As was noted previously the range of most practical combinations of the shape parameters is arbitrarily defined as containing all sets for which maximum variation in the mooring force is within 20 percent of the lowest attainable value of maximum variation for the given draft, displacement etc. In Figures 15 to 23 this range was defined by the shaded regions. Through the use of curve fitting techniques, the range of practical values of r for each value I, may be suitably approximated by

(14)
$$\left[r_{by} - (0.3441\frac{k}{ft^2}) \cdot \frac{H^2}{B}\right] \leq r \leq \left[r_{bt} + (34.41\frac{k}{ft}) \cdot \frac{H}{B}\right]$$

where r_{bt} is defined by formula (10).

The empirical formulae (10) to (14) which define the best or most practical combinations of shape parameters are in terms of r and L, only. The ratio p corresponding to each combination of r and L, is determined directly from the values of

r and L, but depends on the overall float configuration. For the general bottle shape (Figure 7), p is given approximately by

(15)

$$p=\frac{1}{\left[\frac{(4r^2+2r+23)}{30}+\left(\frac{L}{H}-\frac{3}{10}\right)(r^2-1)\right]}$$

For other practical configurations, the value of p will not be significantly different as long as R_1 is always the maximum radius of the bottle, R_0 is the bottle radius at still water level and L is the height of the annular, or auxiliary, portion measured from the lowest point on the bottle.

Previously, the best design draft for a given maximum design wave height was determined by the ratio ($h_{max}/H=0.8$). If this specific value is chosen for the ratio, the best selection of the shape parameters is given by (10) and the most practical range of shape parameters is given by (14), where C and n are determined specifically by

(16)

$$C=(0.4265)-\frac{(29.775')}{H}+\frac{(367\ 0.4^k)}{B}-\frac{B}{(895{,}310^k)}$$

(17)

$$n=-(0.088)+\frac{H}{(226.76')}+\frac{(3928.5^k)}{B}$$

The selection of an exact maximum design wave height is somewhat ambiguous. The simple wave theory employed in this study is approximate, but suitable. There are other wave theories which would render slightly different results for a specific maximum design wave height and platform size. Therefore, it is more practical to speak of a range of shape parameters in which the best selection of shape parameters are contained; but, by this definition, the best combination of parameters is not specified exactly.

For example, if it is impossible to say the ratio (h_{max}/H) is exactly 0.8, but the designer is reasonably confident that this ratio is bounded by

(18)

$$0.75\leq h_{max}/H\leq 0.85.$$

The present method then teaches that the designer is reasonably certain of designing the best configuration if for a given value of L, r_{bt} is bounded by

(19)

$$r_1\leq r_{bt}\leq r_2$$

where

(20)

$$r_1=1+\left[C_1/\left(\frac{L}{H}\right)\right]^{n_1}$$

(21)

$$C_1=(0.4261)-\frac{(29.775')}{H}+\frac{(3441^k)}{B}-\frac{B}{(1{,}018{,}670^k)}$$

(22)

$$n_1=-(0.088)+\frac{H}{(215.8')}+\frac{(3928.5^k)}{B}$$

and

(23)

$$r_2=1+\left[C_2/\left(\frac{L}{H}\right)\right]^{n_2}$$

(24)

$$C_2=(0.4271)-\frac{(29.775')}{H}+\frac{(3900^k)}{B}-\frac{B}{(793.080^k)}$$

(25)

$$n_2=-(0.088)+\frac{D}{(238.9')}+\frac{(3928.5^k)}{B}$$

Moreover, the range of "most practical" combinations of shape parameters, the shaded regions, becomes the "union" of all regions defined by (14) for all values of (h_{max}/H) which are bounded by (18). More specifically, the range of "most practical" values of r for each L is bounded by

(26)

$$\left[r_1-(0.3441\frac{k}{ft^2})\frac{H^2}{B}\right]\leq r\leq\left[r_2+(34.41\frac{k}{ft})\frac{H}{B}\right].$$

Previously the acceptable or practical range for the ratio h_{max}/H was approximately

(27)

$$0.65\leq(h_{max}/H\leq 1.00).$$

For a ratio smaller than 0.65 there would be too much structure for the maximum design wave height, and consequently, the structure becomes unnecessarily expensive. If the ratio is greater than 1.00, there is too small a structure for the maximum design wave height, and consequently, the maximum variation in mooring force becomes too great. Therefore, the best selection of draft is such that the ratio (h_{max}/H) is bounded as in (27). Under this condition, the best selection of shape parameters is bounded by

(28)

$$r_3\leq r_{bt}\leq r_4$$

where

(29)

$$r_3=1+\left[C_3/\left(\frac{L}{H}\right)\right]^{n_3}$$

(30)

$$C_3=(0.4261)-\frac{(29.775')}{H}+\frac{(2982.2^k)}{B}-\frac{B}{(1{,}356{,}200^k)}$$

(31)

$$n_3=-(0.088)+\frac{H}{(196.7')}+\frac{(3928.5^k)}{B}$$

and

(32)

$$r_4=1+\left[C_4/\left(\frac{L}{H}\right)\right]^{n_4}$$

(33)

$$C_4=(0.4305)-\frac{(29.775')}{H}+\frac{(4588^k)}{B}-\frac{B}{(573{,}000^k)}$$

(34)

$$n_4=-(0.088)+\frac{H}{(284.7')}+\frac{(3928.5^k)}{B}$$

The maximum variation in mooring force is reasonably acceptable if the shape parameters fall within the bounds set forth by (28) to (34) above. However, it must also be recognized that the very best design may not have been defined.

The range of "most practical" values of r for each L is bounded by

(35)

$$\left[r_3-(0.3441\frac{k}{ft^2})\frac{H^2}{B}\right]\leq r\leq\left[r_4+(34.41\frac{k}{ft})\frac{H}{B}\right]$$

This range comprises the union of all combinations of shape parameters which are defined as the most practical combinations by formulae (10) to (14) for values of (h_{max}/H) satisfying (27).

Attention is directed to Figure 3 which is taken along the line 3—3 of Figure 1. This Figure shows four vertical floats arranged in a square and connected by cross bracing 34. As can be seen, there are four riser pipes 28A which extend upwardly through these vertical floats to the deck 12. Derrick 14 supports drilling equiment which is used to drill holes in the ocean floor through these riser pipes 28A. The well head equipment, including blowout preventers, etc., can be located at the surface. From the arrangement of Figure 3, it will be seen that as many as 16 wells can be conveniently drilled from this one structure. After the wells are drilled, the structure can, if desired, remain at the location and be used as a production gathering facility.

Figure 2 illustrates how the upper portions 28A of the riser pipes extend through the lower end member 42 of section 20 of the float. These pipes are rigidly attached, as by welding, to such floats or portions of the structure so that the structure is rigidly connected to the ocean floor by the pipes 28A.

The predominating vertical forces acting on a properly designed, vertically moored platform are associated with inertia and acceleration phenomena. It is illustrative to separate these vertical forces into two categories: namely, variable buoyancy and vertical water acceleration forces. The two categories of forces act in opposite directions, and it is important to balance the forces to give as small a variation in the mooring force as possible. In achieving the desired balance, it may for some designs be desirable to increase or adjust the accceleration force acting on the platform. The acceleration force can be increased by the provision of fins 50. Recognize that acceleration forces are associated with volumes of displaced and therefore accelerated water. The effect of the fins is to trap a surrounding "hydrodynamic mass" or volume of water. In this way the acceleration forces may be increased by opening of the fins to entrap more of the hydrodynamic mass. On the other hand, when the fins are folded into a vertical position, they do not influence the acceleration forces.

The installation of the vertically moored platform might typically be done according to the following steps:

1. Launch, or otherwise remove the base plate 22 from a transportation barge.
2. Lower the base plate 22 to the ocean floor by means of guidelines.
3. Using a semi-submersible drilling unit drive anchor piles 24 (e.g., of 30 inches in diameter) through the base plate following conventional underwater drilling practice.
4. Drill out through the anchor piles 24 to receive 20-inch diameter casing.
5. Run 20-inch diameter casing with the lower portion of ball joint 32 at the top of the casing.
6. Cement casing in the well.

7. Repeat the operation for other anchor piles and casings installed in the base plate.

8. Bring platform 10 to the location.

9. Ballast the plaform to float at the designed draft.

10. Using, for example, derrick 14, run elongate members 28 in the manner normally employed for installing marine risers, passing the elongate members through vertical pipes down through the platform.

11. Make up ball joint 32 at the bottom of each elongate member 28.

12. Weld off, or otherwise fix, the top of elongate members 28 at the platform deck.

13. Deballast the platform 10 in order to apply the proper tension to the elongate members 28.

WHAT WE CLAIM IS:—

1. A floating structure having limited lateral movement for use in a body of water having an expected maximum wave, said structure comprising a platform including a working deck, and buoyancy means for supporting said working deck, anchor means for securing the structure to the floor of said body of water, horizontally spaced-apart, parallel, elongated members anchoring said platform to said anchor means, said platform in use being free of any anchoring connection with the floor of the body of water other than said parallel elongated members, said buoyancy means having a first volume below the still water line and above the trough of said expected maximum wave, said first volume having a cross-sectional area obtained by dividing the said first volume by the depth of the trough, and a second volume below the trough said second volume being equivalent to a third volume and a fourth volume, said third volume being equal to the vertical dimension of said buoyancy means below the trough times said cross-sectional area, said fourth volume being equivalent to the second volume minus the third volume, and said fourth volume being between about 20 and about 60 percent of the total displacement of the buoyancy means.

2. The structure according to claim 1, wherein said buoyancy means comprises a plurality of spaced float members, positioned vertically with respect to the working deck, each float member comprising said first and second volumes, said first and third volumes resulting from a columnar shape having a combined volume between about 40% to about 80% and preferably between about 40% to about 60% of the total displacement of the float members.

3. The structure according to claim 1 or 2, wherein the ratio h_{max}/H is 0.8 in which h_{max} is the height of an expected maximum wave and H is the still water draft.

4. The structure according to claim 1, 2 or 3, having a still water draft between 75 and 150 feet.

5. The structure according to claim 2, 3 or 4, including pivotal means connecting the lower ends of the elongated members with the anchor means, and additional pivotal means connecting the upper ends of the elongated members with the float members.

6. The structure according to any one of claims 2 to 5, including fins attached to the lower portion of the float members, and means for moving the fins about a horizontal axis.

7. The structure according to any one of claims 2 to 6, including cross bracing between the float members and below the still water line.

8. The structure according to claim 1, wherein said buoyancy means comprises at least three float members, the combined volume of said first and third volumes being between about 45% and about 65% of the total displacement of the float members and said fourth volume being exterior of the third volume and comprising between about 55% and about 35% of the total displacement of the float members below still water.

9. The structure according to claim 8, including a ratio h_{max}/H which is between 0.65 and 1.00 where h_{max} is the expected maximum wave height and H is the still water draft.

10. The structure according to any one of claim 2 to 9, wherein each fourth volume is at least partially cylindrical and surrounds a part of each third volume, said float members having a total still water displacement B, a still water draft H, each first and third volumes having a combined overall vertical length L, and the float members is defined by parameter value r, the parameter value r being the ratio of

* C L M S *

7. Repeat the operation for other anchor piles and casings installed in the base plate.

8. Bring platform 10 to the location.

9. Ballast the plaform to float at the designed draft.

10. Using, for example, derrick 14, run elongate members 28 in the manner normally employed for installing marine risers, passing the elongate members through vertical pipes down through the platform.

11. Make up ball joint 32 at the bottom of each elongate member 28.

12. Weld off, or otherwise fix, the top of elongate members 28 at the platform deck.

13. Deballast the platform 10 in order to apply the proper tension to the elongate members 28.

WHAT WE CLAIM IS:—

1. A floating structure having limited lateral movement for use in a body of water having an expected maximum wave, said structure comprising a platform including a working deck, and buoyancy means for supporting said working deck, anchor means for securing the structure to the floor of said body of water, horizontally spaced-apart, parallel, elongated members anchoring said platform to said anchor means, said platform in use being free of any anchoring connection with the floor of the body of water other than said parallel elongated members, said buoyancy means having a first volume below the still water line and above the trough of said expected maximum wave, said first volume having a cross-sectional area obtained by dividing the said first volume by the depth of the trough, and a second volume below the trough said second volume being equivalent to a third volume and a fourth volume, said third volume being equal to the vertical dimension of said buoyancy means below the trough times said cross-sectional area, said fourth volume being equivalent to the second volume minus the third volume, and said fourth volume being between about 20 and about 60 percent of the total displacement of the buoyancy means.

2. The structure according to claim 1, wherein said buoyancy means comprises a plurality of spaced float members, positioned vertically with respect to the working deck, each float member comprising said first and second volumes, said first and third volumes resulting from a columnar shape having a combined volume between about 40% to about 80% and preferably between about 40% to about 60% of the total displacement of the float members.

3. The structure according to claim 1 or 2, wherein the ratio h_{max}/H is 0.8 in which h_{max} is the height of an expected maximum wave and H is the still water draft.

4. The structure according to claim 1, 2 or 3, having a still water draft between 75 and 150 feet.

5. The structure according to claim 2, 3 or 4, including pivotal means connecting the lower ends of the elongated members with the anchor means, and additional pivotal means connecting the upper ends of the elongated members with the float members.

6. The structure according to any one of claims 2 to 5, including fins attached to the lower portion of the float members, and means for moving the fins about a horizontal axis.

7. The structure according to any one of claims 2 to 6, including cross bracing between the float members and below the still water line.

8. The structure according to claim 1, wherein said buoyancy means comprises at least three float members, the combined volume of said first and third volumes being between about 45% and about 65% of the total displacement of the float members and said fourth volume being exterior of the third volume and comprising between about 55% and about 35% of the total displacement of the float members below still water.

9. The structure according to claim 8, including a ratio h_{max}/H which is between 0.65 and 1.00 where h_{max} is the expected maximum wave height and H is the still water draft.

10. The structure according to any one of claim 2 to 9, wherein each fourth volume is at least partially cylindrical and surrounds a part of each third volume, said float members having a total still water displacement B, a still water draft H, each first and third volumes having a combined overall vertical length L, and the float members is defined by parameter value *r*, the parameter value *r* being the ratio of

the maximum radius of the fourth volume to the radius of the third volume, which value r is between

$$[r_3-(0.3441\frac{\text{kips}}{\text{Ft}^2})\ (H^2/B)]$$

and

$$[r_4+(34.41\frac{\text{kips}}{\text{Ft}})\ (H/B)]$$

where r_3 is determined from equations (29) through (31) and r_4 is determined from equations (32) through (34), and wherein the total displacement, platform weight, and still water mooring force is measured in kips.

11. The structure according to any one of claims 2 to 9, wherein each fourth volume is at least partially cylindrical and surrounds a part of each third volume and wherein the float members provide a total still water displacement B and a still water draft H, each first and third volumes having a combined overall vertical length L, and the shape of the float member is defined by a parameter value of r, the parameter value r being the ratio of the maximum radius of the fourth volume to the radius of the third volume, which value r is between

$$[r_1-(0.3441\frac{\text{kips}}{\text{ft}^2})\ (H^2/B)]$$

and

$$[r_2+(34.41\frac{\text{kips}}{\text{ft}})\ (H/B)]$$

where r_1 is determined from equations (20) through (22) and r_2 is determined from equations (23) through (25), and wherein the total displacement, platform weight, and still water mooring force is measured in kips.

12. The structure according to any one of claims 2 to 9, wherein each fourth volume is at least partially cylindrical and surrounds a part of each third volume and wherein the float members provide a total still water displacement B and a still water draft H, each first and third volumes having an overall vertical length L, and the vertical float member is defined by parameter value r, the parameter value r being the ratio of the maximum radius of the fourth volume to the radius of the third volume, which value r is between

$$[r_{bt}-(0.3441\frac{\text{kips}}{\text{ft}^2})\ (H^2/B)]$$

and

$$[r_{bt}+(34.41\frac{\text{kips}}{\text{ft}})\ (H/B)]$$

where r_{bt} is determined from equations (10), (16), and (17), and wherein the total displacement, platform weight, and still water mooring force is measured in kips.

13. The structure according to any one of claims 2 to 12, wherein the buoyancy means provides a total still water displacement between 15,000,000 and 60,000,000 pounds, the shape of each vertical float member being defined by either (a) values of p and r which when plotted as a point fall into the shaded regions of Figures 15B to 23B or fall into the shaded regions obtained by a linear interpolation between the shaded regions of these figures, said interpolation being made on the basis of still water displacement and still water draft, where (p) is the ratio of the displacement of the first volume to the total displacement, or (b) values of (L/H) and r which when

plotted as a point fall into the shaded regions of Figures 15A to 23A, or fall into shaded regions obtained by a linear interpolation between the shaded regions of these figures, said interpolation being made on the basis of still water displacement and still water draft.

14. A floating structure constructed and adapted to operate substantially as herein described with particular reference to the embodiments illustrated in the accompanying drawings.

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